

Human space flight and future major space astrophysics missions: servicing and assembly

Harley Thronson^{*a}, Bradley M. Peterson^b, Matthew Greenhouse^a, Howard MacEwen^c, Rudranarayan Mukherjee^d, Ronald Polidan^e, Benjamin Reed^a, Nicholas Siegler^d, and Hsiao Smith^a

^aNASA Goddard Space Flight Center, Greenbelt, MD USA 20771; ^bSpace Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218; ^cReviresco LLC, 4901 Loosestrife Ct., Annandale, VA 22003-4048; ^dNASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109; ^ePolidan Science Systems & Technologies, LLC, 3884 NW Orchard Ct, Suite 100, Terrebonne, OR 97760

ABSTRACT

Some concepts for candidate future “flagship” space observatories approach the payload limits of the largest launch vehicles planned for the next few decades, specifically in the available volume in the vehicle fairing. This indicates that an alternative to autonomous self-deployment similar to that of the James Webb Space Telescope will eventually be required. Moreover, even before this size limit is reached, there will be significant motivation to service, repair, and upgrade in-space missions of all sizes, whether to extend the life of expensive facilities or to replace outworn or obsolete onboard systems as was demonstrated so effectively by the Hubble Space Telescope program. In parallel with these challenges to future major space astronomy missions, the capabilities of in-space robotic systems and the goals for human space flight in the 2020s and 2030s offer opportunities for achieving the most exciting science goals of the early 21st Century. In this paper, we summarize the history of concepts for human operations beyond the immediate vicinity of the Earth, the importance of very large apertures for scientific discovery, and current capabilities and future developments in robot- and astronaut-enabled servicing and assembly.

Keywords: Human space flight, Hubble Space Telescope, space astronomy, space assembly, space robotics, space servicing

1. BACKGROUND

1.1 Challenges to achieving future major goals in space astrophysics

Whether improving the clarity of images, increasing the sample size of candidate exoplanets, or improving signal-to-noise ratios of point sources, space telescope performance increases with a high power of the aperture, D . Signal-to-noise ratios, for example, vary as D^2 to D^4 , depending upon the type of source being observed or the effects of background emission. Improved angular resolution can be achieved by using techniques such as interferometry, although for faint-object astronomy, physics unambiguously dictates that total photon-collecting area is the key parameter. For that reason, astronomers, engineers, and technologists have devoted enormous resources to finding ways of designing and launching ever-larger telescopes. At present, the James Webb Space Telescope (JWST), with its diameter of 6.5 meters, is the current state of the art for large space telescopes.

The scientific motivation for larger apertures is readily apparent in the growth of ground-based observatories. There has been a rapid expansion of aperture from the 5-meter Palomar telescope (1948), to the W. M. Keck 10-meter telescopes (1993), to the Thirty Meter Telescope (TMT) and the ~39-meter European Extremely Large Telescope (EELT) that are both in development with first light planned for the early/mid-2020s. These giant telescopes have revolutionized and will continue to revolutionize astrophysics.

In early 2016, NASA’s Astrophysics Division (APD) identified a quartet of concepts for science and technology development for future “strategic missions”¹. Science and technology definition teams have been assigned to each of

these mission concepts for the purpose of developing science justification and requisite technology needs. This information will be required to bring these concepts to a state of maturity that will allow them to be recommended by NASA for consideration by the National Academies' 2020 Decadal Survey of Astronomy and Astrophysics as possible major missions to be initiated following the Wide Field Infrared Survey Telescope (WFIRST) mission a decade or so from now. At least one of the mission concept designs already approaches the limit of the largest fairing envisioned for the Space Launch System (SLS) Block II vehicle. That is, to achieve science goals that require even larger apertures, an alternative to autonomous deployment must be developed.

The primary objective of the NASA astrophysics space observatories is to provide the science community access to the electromagnetic spectrum that does not penetrate the Earth's atmosphere. Meeting this objective requires several concurrently operating flight assets each of unique architecture that is driven by the physics of operating in a given region of the spectrum. NASA's Great Observatory Program was NASA's first success in achieving this goal. Its concurrent assets are HST, Chandra, and Spitzer, covering the wavelengths from x-ray into the infrared.

Cost constraints require that the most ambitious missions are developed in series, with development times in the range of 15-20 years for large JWST-class facilities. Hence, in order to achieve concurrent operation, the individual assets must achieve very long service life. The Great Observatory Program, initiated in the 1990s, was made possible to a large degree by regular servicing of HST, currently in its 28th year of operation. If more than one or two major space observatories are required to be in operation simultaneously, operational lifetimes will have to be in the range of a half-century, which is by no means unusual for ground-based telescopes and made possible by regular upgrades and system improvements.

1.2 Meeting the challenges to future major space observatories

All four of the future NASA "flagship" mission concepts, as well as WFIRST, are the first to be subject to the Congressional requirements in the "National Aeronautics and Space Administration Authorization Act of 2010" (PL 111-267):

The Administrator shall continue to take all necessary steps to ensure that provisions are made for in-space or human servicing and repair of all future observatory-class scientific spacecraft intended to be deployed in Earth-orbit or at a Lagrangian point to the extent practicable and appropriate. The Administrator should ensure that agency investments and future capabilities for space technology, robotics, and human space flight take the ability to service and repair these spacecraft into account, where appropriate, and incorporate such capabilities into design and operational plans.

In other words, Congress has instructed NASA to both make its future major space astronomy missions serviceable "if practicable and appropriate," while also simultaneously investing in the operations and capabilities to make this possible. Leveraging some of the most significant benefits of the HST experience, Congress has challenged NASA specifically to develop the capabilities to extend the lifetime and/or update the instrumental capabilities of its future major astrophysics missions.

Fortunately, to meet this challenge three major developments in the coming decade are likely to profoundly alter – and significantly enhance – how the largest space observatories will be deployed in space. The engineering and scientific communities should together be prepared to take advantage of:

- Substantial decrease in the cost of medium-lift launch vehicles (e.g., the SpaceX Falcon series, Blue Origins) that is likely to permit cost-effective delivery to orbit of spacecraft components, such as precision mirrors and other observatory components,
- Continuing advancement of the capabilities of space robotics/telerobotics, and
- NASA's post-ISS human space flight goals for the next decade, specifically the deployment of a long-duration habitation and operations facility (aka, the "Gateway") at cis-lunar locations such as Earth-Moon L1,2 locations or equivalent.

The purpose of this paper is to provide a summary of work to date on post-ISS, post-HST concepts for servicing, upgrading, and assembling major space observatories beyond the immediate vicinity of the Earth, typically at one of the Sun-Earth-Moon libration points or their equivalent. For a recent compilation of presentations, images, and reports on these concepts, the reader is referred to <https://asd.gsfc.nasa.gov/fasst/>. In addition, a number of concepts for servicing and assembly in space were published in the October 2016 issue of the SPIE *Journal of Astronomical Telescope and Instrument Systems*.

2. A BRIEF HISTORY OF POST-HST SERVICING AND ASSEMBLY CONCEPTS

Not surprisingly, what was probably the earliest account of cis-lunar servicing, in a manner of speaking, was by Arthur C. Clarke in his award-winning 1961 science fiction novel, *A Fall of Moondust*. In this engaging tale, a “brilliant, but eccentric” astronomer in an Earth-Moon (E-M) libration-point habitation and operations facility observes and subsequently organizes the rescue of a lunar-surface tourist excursion trapped when a cavern collapses beneath them.

More presciently and relevant for this paper was the theoretical study about a decade later by Robert Farquhar² who developed a series of libration-point scenarios for lunar exploration and cis-lunar operations by astronaut and robotic systems, including lunar far-side exploration as an option for the final missions in the Apollo Program. [History records that proposed far-side lunar exploration by astronauts during the Apollo Program was rejected.]

Probably the two most significant early studies of astronaut-enabled servicing and assembly beyond low-Earth orbit (LEO) were a late-1990s Boeing concept for telerobotic assembly of JWST (*née* the Next Generation Space Telescope (NGST)) and the 1999 – 2001 Decadal Planning Team (DPT) architecture for NASA that interweaved both human space flight and science into a single strategy for the Agency’s future.

The Boeing concept³ for telerobotic assembly of a 10-meter JWST-type observatory at a Sun-Earth (S-E) L2 location summarized the advantages and disadvantages of such a scenario that presaged those widely recognized over the subsequent two decades (verbatim extracts from the Boeing report with our comments in brackets):

Advantages to in-space assembly of large space optics:

- The diameter of a robotically assembled NGST telescope will be constrained primarily by cost and weight, not by launch vehicle shroud volume
- Higher probability for a successful robotic assembly [Compared with the poorly known, at the time, capability for precision autonomous deployment.]
- Packaging prevents mirror contamination [Packaging also relaxes materials properties related to surviving launch loads]
- A larger aperture [enabled by space assembly] will return more science
- Some servicing of the NGST during its lifetime is possible [In the Boeing concept, the telerobot was launched with the pieces of the observatory.]

Disadvantages to in-space assembly of large space optics

- The [additional] cost of robots
- The weight of the robots [Advances in artificial intelligence, materials, and robot architectures have reduced this issue significantly]

Shortly after the Boeing report was completed, NASA and the Office of Management and Budget (OMB) established the DPT, which produced over about three years a series of architectures, technology development plans, costs, and milestones for a program of astronaut operations and science goals intended eventually to lead to initial human missions to Mars.⁴ Notable in these architectures was the role of what the DPT dubbed “Gateway” at an E-M L1,2 venue, which would be the first major human space flight goal after ISS. Assembly, repair, refueling, and upgrading of science

missions would take place at this facility, which would also develop capabilities necessary for very long-duration human missions. [See Figure 1]

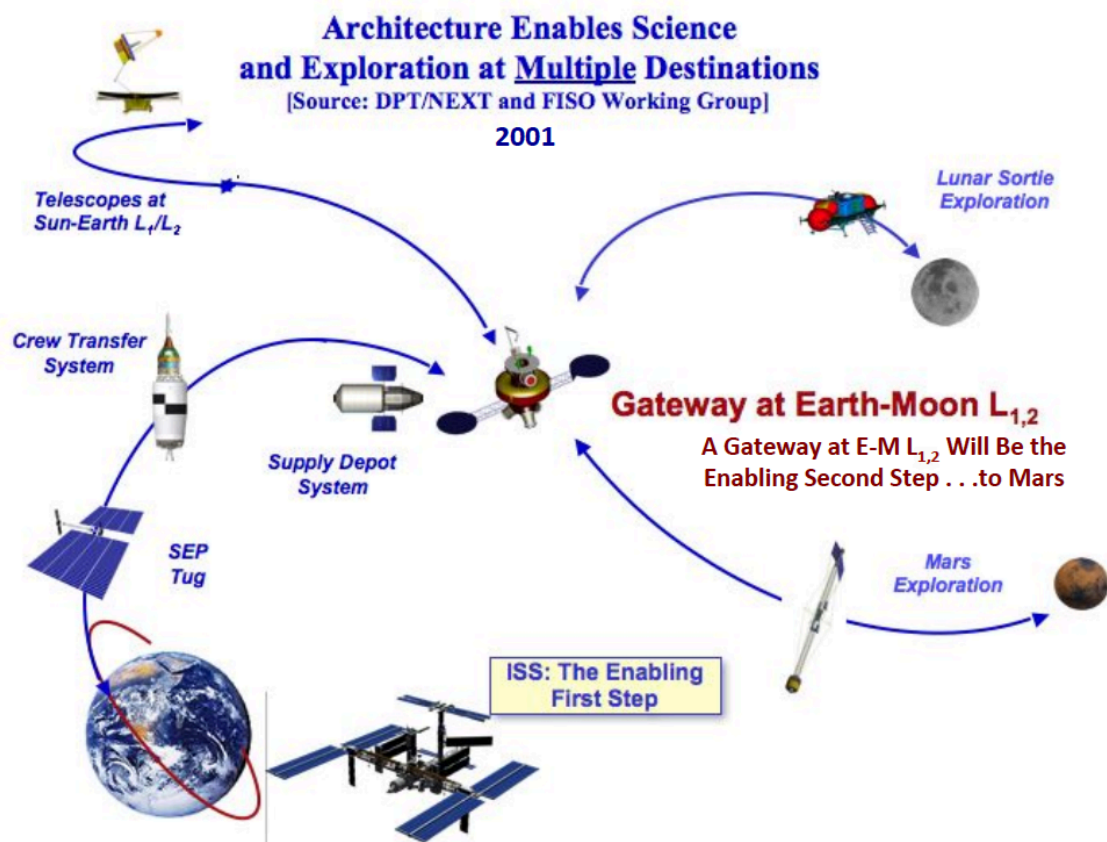


Figure 1. Decadal Planning Team (DPT) architecture proposed in 2001 to NASA and OMB to unify NASA science and human space flight to achieve goals not otherwise possible separately. The proposed strategy was based upon a long-duration multi-purpose habitation and operations site at an Earth-Moon $L_{1,2}$ venue. [See Reference 4]

Although the DPT-developed architecture, technology investment plan, and an integrated science+human space flight strategy was not adopted by NASA, the concept of eventual astronaut- and/or robot-assisted assembly and servicing of major science facilities beyond the immediate vicinity of the Earth became a recurrent theme within NASA strategic planning.

Some years after NASA HQ disbanded the DPT, scenarios for adapting NASA's new Constellation Program architecture, developed about a decade ago, were widely discussed, even though – in contrast to the case with DPT – science and human space flight were not integrated into a unified NASA-wide program. Consequently, scientists and engineers assessed largely independently of NASA how the Constellation Program might be adapted to achieve major science goals. For example, in 2008, a small joint Lockheed Martin/NASA Goddard Space Flight Center team produced a concept⁵ to service a hypothetical large-aperture observatory using a minimum number of elements of the Constellation Program architecture. This scenario was intended to be an early demonstration mission in advance of subsequent more ambitious assembly capabilities in space. [See Figure 2] A year later, the National Academies published its influential *Launching Science: Science Opportunities Provided by NASA's Constellation Program*.⁶ This report included an extensive discussion of positive and negative aspects of space assembly and servicing, which remains relevant today.

By the latter part of the last decade, with a series of successful HST servicing missions and final assembly of ISS, sufficient experience was available to justify a major workshop⁷ – and report – on options and alternatives for future space servicing from the immediate vicinity of the Earth to the Sun-Earth-Moon libration points, prepared and circulated in time for consideration by the National Research Council's 2010 Decadal Survey in Astronomy and Astrophysics. However, space servicing and assembly did not appear prominently in that Survey.

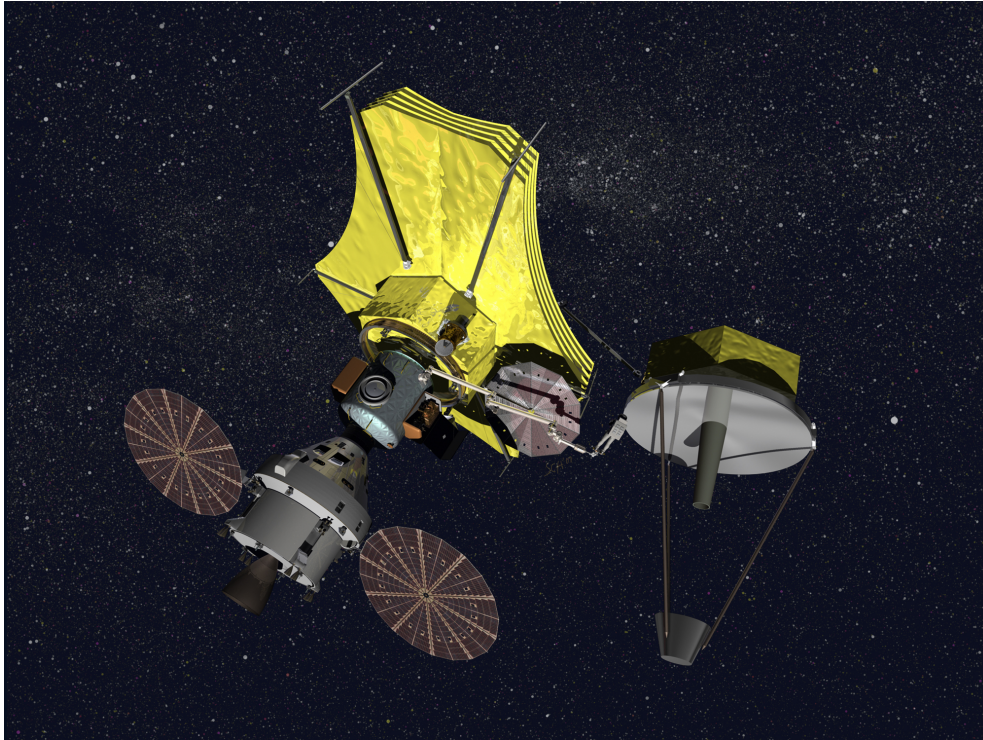


Figure 2. Concept developed in advance of the 2010 NRC Decadal Survey in Astronomy and Astrophysics to use an Orion Crew Exploration Vehicle, along with an airlock/habitation module and robotic arm, for a multi-week servicing and upgrade mission to a major observatory. [See Reference 5]

3. RECENT CONCEPTS TO ENABLE SPACE ASSEMBLY AND SERVICING

Since the successful series of HST servicing and ISS assembly missions, on-orbit operations to achieve major science goals has continued to expand, developing new capabilities and achieving goals. Examples of the evolution of astronaut and robot servicing are shown in Figure 3.

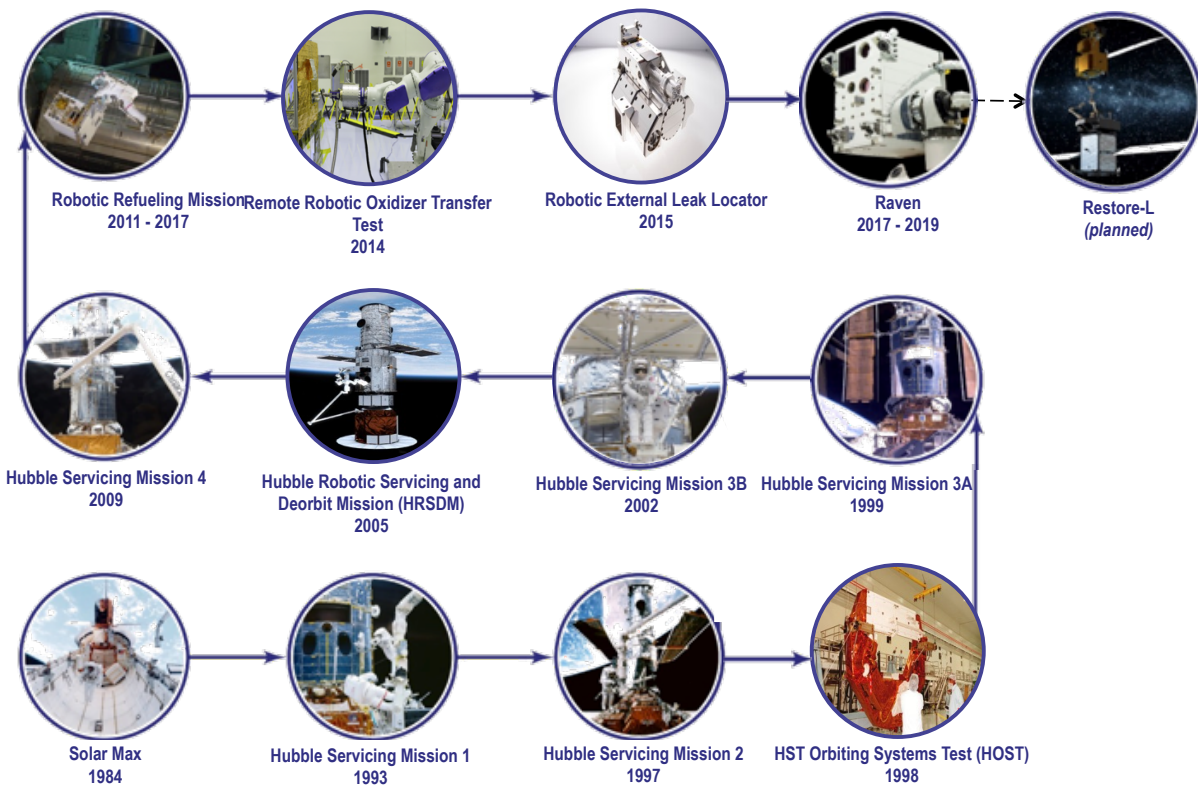


Figure 3. Evolution of NASA's space servicing and assembly. [Courtesy NASA GSFC Satellite Servicing Development Office.]

This development has permitted some increasingly specific guidelines and priorities for new investments to be identified.

3.1 Future medium-lift launch vehicles: declining costs

If future major missions do not need to be launched intact, then fully deployed on orbit, significant cost savings may be realized by using less-costly medium-lift vehicles to launch the elements of observatories (and other facilities) to be assembled once in space. Medium-lift vehicles are not only *per force* less expensive than the heavy-lift vehicles often identified as a requirement for the largest payloads, because of the lack of competition among candidate suppliers (i.e., national space agencies) of the heaviest-lift vehicles, there is little downward pressure on costs-per-launch. Moreover, the heaviest-lift vehicle, the Space Launch System (SLS), will be human-rated, thus guaranteeing a high cost-to-orbit that must be borne at least in part also by non-crewed payloads.

Although the final, full history of decreasing launch vehicle costs has yet to be written, an interesting point was made two years ago by journalist Peter de Selding⁸, who argued that it was the initiative of the French government that Arianespace “all but invented” the commercial launch vehicle business some three decades ago. This opened launch costs to the power of competition and, although not immediately and not always obvious, the costs of medium-lift launch vehicles have generally trended downward over time.

Perhaps the first unambiguous demonstration of a lower-cost medium-lift vehicle was the late-2013 launch by SpaceX of a communications satellite to geostationary orbit on a vehicle for which low prices had been mooted for four years. This in turn led to a number of efforts by competing aerospace companies to match SpaceX, including Arianespace supported by European satellite operators⁹ [See also References 10 and 11.]

No sooner had SpaceX demonstrated success with lower-cost launch vehicles than the company began demonstrating success recovering the first stage of a Falcon vehicle in late 2015. There probably is insufficient data at present to confidently predict whether regular re-use of recovered vehicle elements will produce significant further cost savings, but the intention is there.

3.2 Concepts for astronaut operations beyond the immediate vicinity of the Earth: libration points and similar orbits

Our paper opened with a brief summary of the past three decades of development of concepts for mainly astronaut-enabled servicing and assembly of major space astronomy assets beyond the immediate vicinity of the Earth. In more recent years, with humans in space gaining operational experience in the ISS, there have been increasingly sophisticated concepts for astronaut-enabled satellite assembly and servicing in deeper space.

Over the past two years, NASA's Space Technology Mission Directorate (STMD) has been funding industry-led engineering studies of long-duration habitation and operations sites in cis-lunar space via their NextSTEP activity.¹² Although the facilities designed via this activity are intended primarily to be the next "stepping stone" in human space flight after the ISS, augmenting them with capabilities for robot- and astronaut-enabled servicing and assembly will be an opportunity for an attractive integration of goals of NASA's science and human space flight program. Continuing to develop these designs over the next two years will offer an opportunity for consideration by the National Academies' 2020 Decadal Survey in Astronomy and Astrophysics.

As demonstrated by the construction of ISS and repeated servicing missions to HST, advantages of astronaut-enabled servicing and assembly of complex systems include (1) on-site intelligence and dexterity, (2) a high degree of responsiveness to inevitable unexpected challenges, and (3) versatility in adapting to evolving work plans and schedules. Even without EVA capabilities at a cis-lunar Gateway-type operations facility, astronaut operation of a telerobotics system in the vicinity of a serviceable space observatory will have the advantage of very low latency: near-real time precision control and observation of a delicate and complex optical system. [See also Section 3.3.2]

Early industry concepts for cis-lunar habitation facilities have been presented at, for example, the American Astronautical Society's 2017 Robert H. Goddard Memorial Symposium¹³ and the Explore Mars, Inc. 2017 Humans to Mars Summit,¹⁴ as well as July and August, 2017, Future In-Space Operations (FISO) seminars.¹⁵ Future design work on these concepts will assess EVA and telerobotics options.

3.3 Space robotics: from the Hubble Space Telescope to libration points

3.3.1 In-space servicing systems

Building on the legacy of five successful Hubble Space Telescope (HST) servicing missions, NASA GSFC's Satellite Servicing Projects Division (SSPD) continues to advance the state of the art in robotic servicing. Robotic technology will enable the routine servicing of satellites that were not originally designed to be serviceable. This, in turn, will extend the lifespan of valuable assets, allow for technology upgrades, and help mitigate the persistent problem of orbital debris.

SSPD is currently working on various technologies and projects in robotic servicing. Technologies include a dexterous seven-degree-of-freedom Robotic Servicing Arm that can be used on diverse missions, a relative navigation system that will enable autopilot for spacecraft, propellant transfer technologies to enable refueling, a variety of specialized tools, and cooperative servicing aids which when integrated into satellite designs, will make servicing them easier. Along with these technologies, SSPD has also carried out and continues to develop servicing missions.

In addition to the manned HST servicing missions, SSPD has successfully launched Robotic Refueling Missions (RRM) 1 and 2, and Raven. RRM 1 and 2 were part of a multi-phased International Space Station (ISS) technology demonstration that tested tools, technologies, and techniques to refuel and repair satellites in orbit, especially satellites not designed to be serviced. RRM 3 is scheduled to launch in early 2018 and will continue this work by demonstrating the first-ever transfer of cryogenics and xenon in space, which are important consumables for keeping optical equipment cool, for solar electric propulsion, and for potential application in future human journeys to Mars.

Raven, launched in February 2017, is a technology-filled module on the ISS that will help develop a relative navigation capability for NASA, critical for the autonomous rendezvous portion of robotic servicing and assembly. Raven consists of three sensors, a high-speed processor and advanced algorithms that will work together to independently image and

track visiting spacecraft to the ISS. Raven will image these spacecraft to test the key elements of a new spacecraft autopilot system that, once perfected, can be taken “off the shelf” and integrated into many future NASA missions.

Finally, SSPD’s Restore-L mission will bring together all the individual robotic servicing technologies and capabilities, to refuel for the first time a satellite not designed to be serviced in-orbit. Using a relative navigation system, robotic arms, and various tools, a robotic spacecraft will autonomously rendezvous with, grasp, refuel, and relocate a government-owned satellite to extend its life. Successfully completing this mission will demonstrate a new capability that will allow satellite operators to extend the lifespan of their assets, deriving more value from their original investments. Additionally, the technologies that will be brought to operational status from the Restore-L mission also extend beyond servicing, and can be applied to in-space assembly, and other NASA missions.

While SSPD is developing and perfecting these technologies, it does not intend to be the only organization to service satellites. Rather, SSPD’s plan is to transfer these technologies to domestic entities, thereby jumpstarting an entirely new industry: commercial servicing. For example, this past spring NASA formally began its satellite servicing technology transfer campaign, with its first Technology Transfer Industry Day, held at NASA GSFC.

3.3.2 In-space assembly

In-space robotic assembly is a system-level opportunity that will enable novel approaches to realizing future paradigm-shifting missions of science and exploration. With robotics as a key enabling technology, future telescopes, starshades, large fuel depots, or long-duration habitation and operations sites (aka, Gateways) may no longer be limited by having to be launched as a complete package.

Space robotics have matured over the last decade or so with significant robotic activities already part of the Mars exploration for planetary applications, ongoing efforts in asteroid and/or comet sampling, robotics on the ISS, and planned missions for robotic servicing and/or refueling of spacecraft as described above. Industry has demonstrated a strong interest and willingness to make robotic servicing and assembly a commercial reality. The STMD Tipping Point program in robotic assembly¹⁶ has a portfolio of industry-led tasks relevant to different applications. Industry¹⁷ played key roles in the DARPA Orbital Express¹⁸ that aimed to validate the technical feasibility of robotic, autonomous on-orbit refueling and reconfiguration of satellites. Similarly, DARPA has selected Space Systems Loral-MDA as its commercial partner for the Robotic Servicing of Geosynchronous Satellites (RSGS) program, where “DARPA and SSL seek to develop technologies that would enable cooperative inspection and servicing of satellites in geosynchronous orbit (GEO), more than 20,000 miles above the Earth, and demonstrate those technologies on orbit.”¹⁹ “In parallel with the RSGS partnership, DARPA also intends to provide the government-developed space robotics technology to other interested U.S. space corporations”. A summary of different industry and government efforts for in-space robotic assembly can be found in Reference 20.

More specifically, Lee *et alia*.²¹ proposes a new way to assemble large telescopes with robotic assembly as the key enabler. In this concept, the telescope backplane truss is robotically assembled from Deployable Truss Modules (DTMs) using quick-connect structural and power connectors. As shown in Figure 4, the DTM is a truss component that is stowed during launch and robotically deployed in space, which enables efficiencies of launch mass and volume. The truss is also amenable to robotic adjustments to desired stiffness, by tightening the connectors, or positional accuracy. The DTMs also have connectors for assembly of a mirror module, a self-contained unit consisting of a base plate onto which segmented mirrors, their rigid body actuators and controllers are assembled before launch. As the figure shows, the robot walks along the truss and assembles the mirror modules to the truss. Thus, the robotic assembly of the primary mirror would consist of (a) robotically deploying individual DTMs, (b) incrementally assembling the DTMs to form a trusswork around the spacecraft, (c) post metrology, robotically adjust the truss to desired precision, and (d) incrementally assemble the mirror modules until desired coverage is obtained. Some aspects of this concept have been demonstrated, including “(i) modular structural elements with power and structural inter-connects that have self-contained alignment ability; and (ii) in-lab demonstration of supervised autonomy based robotic assembly of these modular elements into a three-meter truss in a closed-ring configuration”.²²

Alternatively, another approach may be considered, where structural elements (e.g., rods, beams) are launched and robotically assembled in space by either a manufacturing process (e.g., jig welding) or using connectors similar to joints used in terrestrial applications. Another approach is to assemble only a few larger modules, much larger than the mirror

modules or DTMs described above. The modules used in assembling the ISS are yet another example of what may be considered a module. In this case, a servicer robotic spacecraft similar to RSGS or RESTORE-L may be used to bring the individual components together to be connected.

These examples are intended as representative approaches among different concepts for robotic assembly and presented here to motivate the reader to consider the range of enabling possibilities of in-space robotic assembly. They are motivated by ongoing or recent technology development efforts such as the STMD Tipping Point efforts and the DARPA RSGS servicer robotic system, which has potential plans to “upgrade installation”; that is, robotically assemble a new element to an existing spacecraft²³. The capabilities of the ISS robotic system in instrument installation are well understood.

In-space assembly can equally include and benefit from astronaut participation. On one level, the robot acts as an electromechanical system with complete human control from either ground or from a nearby crewed vehicle. Such high bandwidth telerobotic operations are feasible when time-delays are short and appropriate sensing is feasible (e.g., line of sight). Different levels of software features and sensory feedback may be feasible to make the human more cognizant of the robot and its environment. For example, multi-camera situational awareness, force feedback, in-built safety checks, system health monitoring, software based collision checking and warning systems among others. With any kind of reasonable time delay, (e.g., > 0.5 s), high-bandwidth telerobotics with human-in-the-loop becomes challenging, particularly if the assembly task involves multiple contact scenarios.

An alternative approach with low-bandwidth human-supervised autonomous robotics may be attractive, particularly for scenarios where time delay may be a factor. In this case, the robot is enabled with certain level of embedded autonomous behaviors and the human supervises the robot. The human may provide high-level, low-bandwidth instructions (such as scripts) to the robot. The robot has the ability to interpret the high-level instruction from the human and autonomously execute the corresponding lower-level tasks consistent with the human instruction. However, the human operator has the opportunity to monitor the robotic activity and intervene to correct any off-nominal scenarios. This paradigm has worked well for planetary exploration robotics, such as the Mars rover and lander missions.

Compared to the Martian robotic missions, in-space assembly is likely to be a more structured solution, with assembly more “modularized” through detailed pre-launch design and planning. For example, in the scenario where all elements are to be assembled, the robotic assemblers may carry optical fiducials or sensors for pose estimation taking advantage of models of all elements known beforehand, the lighting conditions controlled using an embedded illumination, and the nature of the interaction loads understood through prior testing. However, uncertainty may still remain from the space environment such as thermal fluctuations, spacecraft dynamics, sensor calibration drift, changes in the post-launch loads components, and, of course, unknown-unknowns.

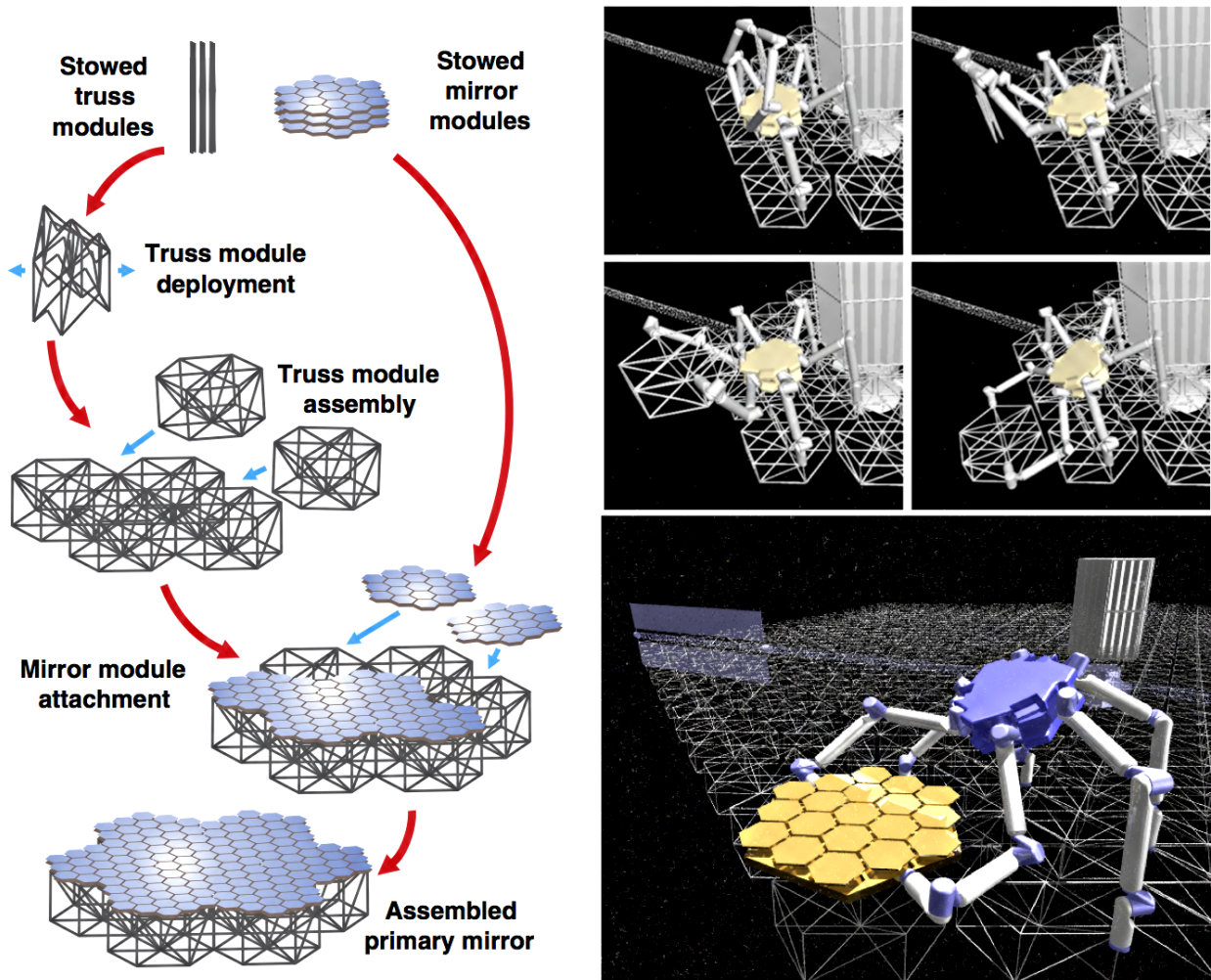


Figure 4. Overall scheme for assembly, shown on the left, demonstrates the different steps for robotic assembly. The illustrations on the right are graphical rendition of concepts for some of those steps showing DTM and mirror module assembly.

3.4 Example assembly in space: A starshade to enable the search for Earth-like planets

Large surveys searching for spectral features in the atmospheres of the closest exoplanets orbiting in the Habitable Zone of Sun-like stars will require space telescopes with direct-imaging capabilities. The residual uncorrected wavefront aberrations, even with extreme adaptive optics, will limit ground telescopes to contrast sensitivities at visible wavelengths to about 10^{-8} (exo-Earths are expected to require sensitivities of around 10^{-10}).²⁴ To acquire a statistically robust sample size of terrestrial Earth-sized planets to examine for habitability astronomers will have to rely on the direct imaging technique from space telescopes.

The key technology to directly imaging Earth-size exoplanets in the next couple of decades will be starlight suppression via occultors. Internal occultors are known as coronagraphs and external occultors are called starshades. Reaching the detection sensitivities required to image exo-Earths and look for evidence of life in their atmospheres is very challenging. NASA and the exoplanet community does not know enough at this time to decide which of the two approaches will be successful and is advancing both technologies until more is learned.

The recent Exo-S Probe-class concept study²⁵ of a mission that uses a starshade provides an excellent discussion of how a starshade works, as well as a number of useful references. A starshade blocks the light from a target star and forms a deep shadow at the position of an aligned space telescope (see Figure 5). The starlight reflected light from the off-axis planet misses the starshade and is detected at the telescope's image plane without the need for adaptive and beam shaping optics. The starshade's performance is independent of the architecture of the telescope's aperture since the starlight suppression occurs outside of the telescope. This enables large centrally obscured, segmented, on-axis telescope apertures to be used. Envisioning future large segmented telescopes exceeding 20 m, starshades will grow with the telescopes to be (a) large enough to keep the telescope in a dark shadow and (b) far away enough to enable the telescope to probe the nearest regions around the star (the center of the Habitable Zone of a Sun-like star at 20 pc corresponds to a 50 mas angular separation). Hence, a 15-meter space telescope would require a starshade exceeding 150 m travelling at separation distances greater than ~1 million km away from its telescope. It would have an inner working angle of less than 15 mas, capable of probing the Habitable Zones of hundreds of Sun-like stars up to 30 pc away.

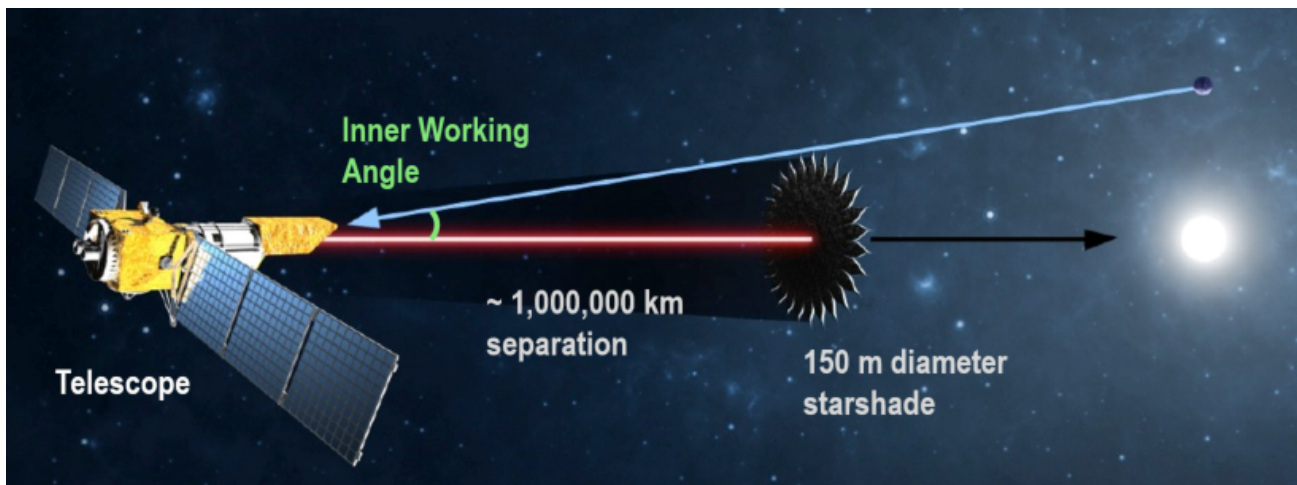


Figure 5. The starshade and its telescope fly in alignment with the target star (not to scale). The starshade blocks the on-axis starlight while simultaneously re-directing the effects of diffraction away from the telescope creating a dark shadow in which the telescope flies. Reflected light from an exoplanet misses the starshade and is collected by the trailing telescope. The starshade along with its analytically-designed petals apodize the oncoming star's wavefront achieving a sensitivity to planets $\sim 10^{10}$ fainter than the star's brightness, enabling the direct imaging of exo-Earths. Radial offsets between the two spacecrafts are relatively loose (~ 1000 km); lateral offsets are much tighter, on order of meters.

A 150-meter starshade would have about two dozen petals each longer than 30 m in length. The biggest petal built to date has been 6 m, which met its structural edge manufacturing envelope of $< 100 \mu\text{m rms}$.²⁶ Stowing two dozen 30 m petals along with an inner disk region exceeding 80 m when fully deployed, would exceed even the 10 m SLS Block 2 fairing volume.

Hence a 150-meter starshade would make an excellent candidate for in-space assembly, as it would be too large to be semi-autonomously deployed from any planned launch vehicle fairing. One concept for in-space assembly would rely largely on robots and is outlined below. Please note the concept outlined here is a representative approach and different architectures for robotic assembly of starshade, as well as with astronaut assistance, are possible. We describe this particular case as a proof-of-concept only for motivational purposes.

Robotic Assembly Concept:

1. The starshade spacecraft bus would launch along with the first supply capsule and dock to a pre-established Gateway-like outpost at the Earth-Moon L1 region. The supply capsule, launched on existing medium-lift launch vehicles, would make several visits during the course of the starshade assembly.
2. The cross-like inner truss of the starshade (Figure 6) is robotically assembled onto the spacecraft bus from the Gateway-like outpost. This inner truss is the backbone of the inner disk region of the starshade. The perimeter truss would be constructed of truss modules delivered by subsequent supply missions, then robotically

assembled using a spider-like robot (see Figure 6). It is from these trusses that the petal interfaces and petals connect.

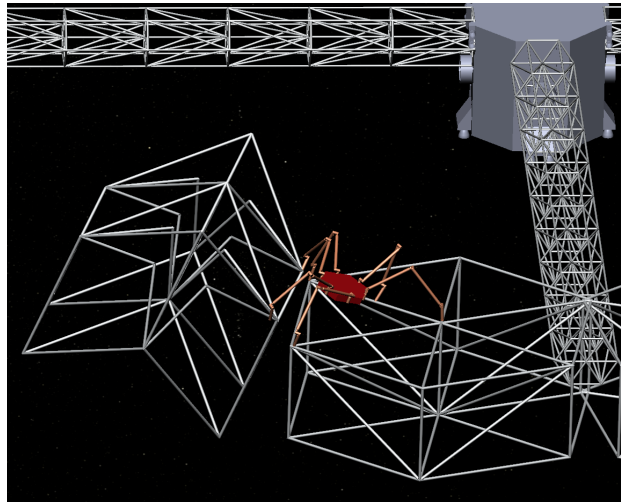


Figure 6. The Multi-Limbed Robot assembles a starshade's perimeter truss modules. These modules are the backing structure for the starshade petals and their interfaces. In the background is the cross-shaped inner truss that serves as the backbone of the starshade. The gray octagonal structure in the upper right portion of the figure represents the starshade spacecraft bus. Not shown is a Deep Space Gateway-like facility that the bus is docked to along with the supply capsules transporting the truss components.

3. The petals (> 30 m long) are robotically assembled (Figure 7) in panelized sections along with their truss interface. Piston actuators that can provide in-plane adjustments to help meet position requirements accompany each petal.

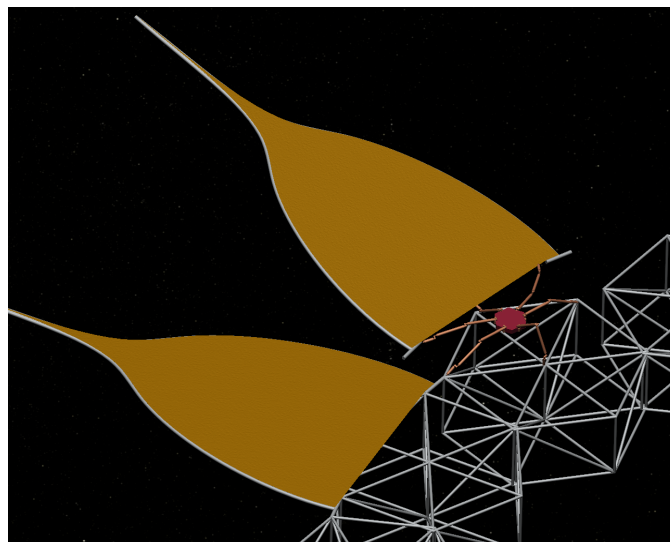


Figure 7. The Multi-Limbed Robot attaches the fully-assembled starshade petals to the perimeter truss modules. The petals themselves are assembled from pre-fabricated sub-panels that are robotically assembled in-situ; the narrow tips are delivered intact and are also robotically assembled.

4. Each petal interface tube stows a portion of the opaque multi-layered inner disk membrane, similar to a rolled carpet. When the petals are all assembled the spider-like robot pulls out the triangular-like membranes similar to pulling a window blind closed (see Figure 8).

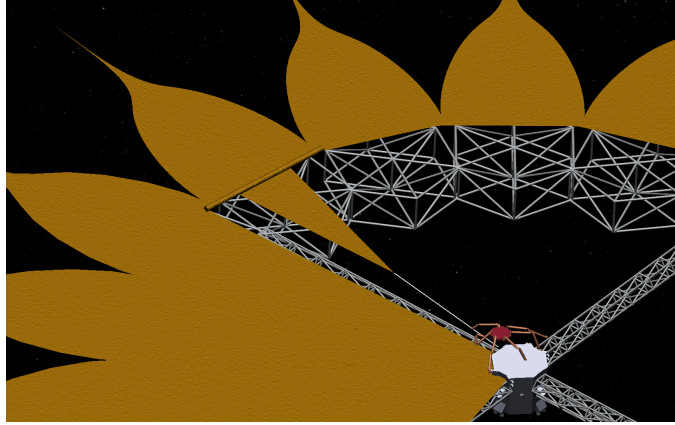


Figure 8. The Multi-Limbed Robot deploys a triangular opaque membrane from an interface tube to fill the inner region of the starshade. The opaque membrane is made up of two thin layers of heat-reflective material separated by a high-density foam. Stitched into the outer layer of the membranes are ultra-thin solar electric panels providing the starshade with solar energy to propel to its stellar targets.

5. The assembly robot is equipped to perform a series of final quality control steps that include laser metrology to confirm the petals' critical shape requirements and sensors to look for any rips in the opaque membrane.
6. The assembly robot returns to the outpost and the starshade is fully assembled (see Figure 9). The starshade can propel itself to the Earth-Sun L2 point with a Δv of only $< 0.5 \text{ km s}^{-1}$, where it will rendezvous with its telescope.

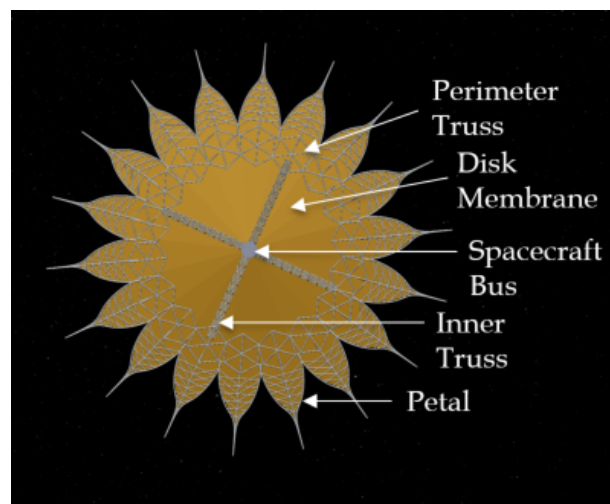


Figure 9. A completed fully assembled 150 m starshade shown with its key modularized assembly items: inner truss, perimeter truss, disk membrane, and petals. Along with its bus, the starshade is now an autonomous-flying spacecraft.

4. CONCLUDING REMARKS

Three major capability developments in the coming decade will make possible the servicing, upgrade, and assembly of the most capable and most challenging future space observatories: (1) advances in robotics and telerobotics, (2) decreasing costs of medium-lift launch vehicles, and (3) plans to extend capable human operations beyond LEO, specifically to cis-lunar space. In addition, together these capabilities will form the basis of strategic engagement among three NASA mission directorates – science, human space flight, and technology – to their mutual benefit, especially on the eve of a new National Academies’ Decadal Survey.

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